Time ripe for superconductivity?

by George Marsh

Commercial applications of superconducting materials have been slow to take off and the early promise of magnetically-levitated trains, compact electric motors of stunning power, and super-efficient power transmission has, in the main, not been met. Recent emergence of power distribution applications in the US and Europe, however, suggests that this could change. At last, it seems, this singular phenomenon, in which electrical resistance becomes vanishingly small in certain materials at extremely low temperatures, could be about to revolutionize the delivery of electricity.

Section of an optical micrograph showing surface of a neodymium cuprate 'buffer' film produced on a nickel substrate using an affordable liquid processing route. (Courtesy of Judith Driscoll, Imperial College.)

But there is a crucial deadline and failure to meet it could send superconductivity back to the commercial shadows (at least outside the medical and scientific niches where it is a key enabler in analytical instruments, magnetic resonance imaging, and particle accelerators) for another 30 years. Later this decade, the vintage infrastructure of dense copper conductors that supports power distribution in developed countries, in particular in the US, will become due for renewal. (Recent power problems in California were largely those of distribution infrastructure.) At the same time, boosting capacity to serve the needs of increasingly affluent populations will pose a challenge. Superconductivity could provide the answer -- if the technology matures in time and cost targets are met.

The race is on. By now 14 000 customers of the Detroit Edison power utility in the US should be receiving their electricity via three 120 m lengths of superconducting cable. In a sub-station in a Frisbie suburb, 110 kg of superconductor have replaced some eight tons of old copper cable. (The installation should have started operating last year, but was delayed for technical reasons not associated with the new cable material.) The superconductor cables occupy just three of nine underground ducts previously taken up by copper, leaving ample room for future expansion. Pirelli Cables has incorporated wire developed and produced by American Superconductor Corporation into the new cable, which is no laboratory sample. Superconductor wire is in production and at a presentation earlier this year, Alex Malozemoff, chief

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technical officer for American Superconductor, briefed US Department of Energy (DOE) officials on the company's new 33 000 m^2 manufacturing facility. Soon Pirelli will supply a kilometer long underground cable based on American Superconductor wire to serve Long Island, New York. Other contracts are in advanced stages of negotiation.

The US is not alone. Last May a program began to power 150 000 homes in Copenhagen via superconductor cables, tests taking place in Tokyo are aimed at a similar result, and more power distribution applications will be announced soon.

Viable wire and tape are key to commercial exploitation in the power sector and several companies are working to bring products to market. A couple of years ago, the Southwire Company hooked up three of its manufacturing plants in Georgia to a main electricity supply using superconducting wire from Intermagnetics General. This has since clocked up some 12 000 hours of service. MicroCoating Technologies (MCT) of Atlanta is working on wire development, while thin film specialist 3M is heading a team aiming to develop superconducting tape under the DOE's national Superconductivity Program for Electric Power Systems. Its partners include Southwire and two DOE national laboratories – Los Alamos and Oak Ridge (ORNL).

Related applications, too, show signs of becoming commercial. American Superconductor recently load tested a 5000 hp motor of only 7.5 m^3 in volume – a fifth the size of an equivalent copper-wired motor – and predicts a revolution in ship propulsion based on the technology. A 100 MW super-generator is being developed by General Electric Company under the DOE's Superconductivity Partnership Initiative (SPI) program. Superconducting wire is at the heart of these and other developments.

Why now?

Superconductivity has a fighting chance of exploiting its window of opportunity, but why has it all come together now? As often happens, the answer is new materials although, paradoxically, it is materials-related issues that have held back progress until recently.

The crucial event was the discovery, 16 years ago by IBM scientists J. Georg Bednorz and K. Alexander Müller, that barium-doped lanthanum copper oxide becomes superconducting at 36 K, some 12 K above the previous record temperature. The subsequent quest for other promising cuprates yielded materials with transition

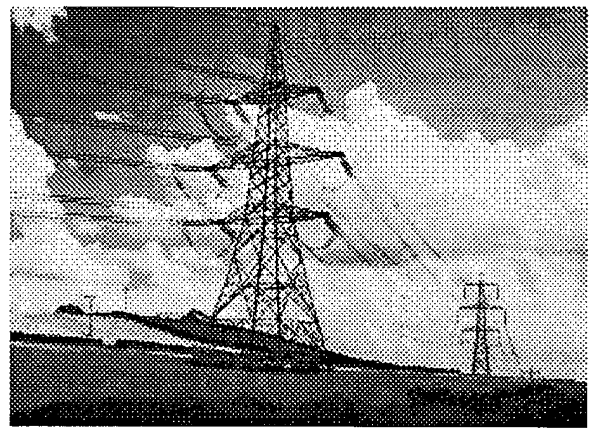

Fig. 1 It may be years before superconductivity has an impact in high-voltage applications like grid transmission at 132 kV, but present developments in lower voltage sectors, such as the Frisbie, Detroit sub-station, and in superconductor magnetic energy storage systems (SMES) could show the way. (Courtesy of National Grid, UK.)

temperatures of up to 130 K. Since nitrogen becomes a liquid at 77 K, several cuprate superconductors could be used with this cheaply available coolant rather than the liquid helium or mechanical cryogenic coolers required to bring temperatures down to low-temperature superconductor levels. Pumped liquid nitrogen is a proven and accessible technology, and ideal for high-temperature superconductors (HTS).

As David Caplin from the Centre for High Temperature Superconductivity at London's Imperial College explains, HTS are of two main families – the bismuth-strontium-calcium-copper oxide (BSCCO) phases which, because it has proved possible to produce them in useful lengths, are the basis of most first-generation wires and tapes now becoming available; and the rare earth-cuprate family (best known is yttrium-barium-copper oxide or YBCO) which, though offering superior performance, is still resisting attempts to produce it in long continuous lengths.

BSCCO cables from American Superconductor and others are configured as several wire filaments grouped round a central tube through which liquid nitrogen is pumped. A major difficulty with BSCCO is that the material, a complex metal oxide that behaves like a ceramic, is about as resilient as eggshells, so its ability to bend is severely limited. This has been overcome by surrounding filaments of it with the highly pliable metal silver, the resulting construct then being flattened into a thick 'tape' for winding into the final cable. Greg Yurek, then a metallurgist with the Massachusetts Institute of Technology, announced in 1987 a method of

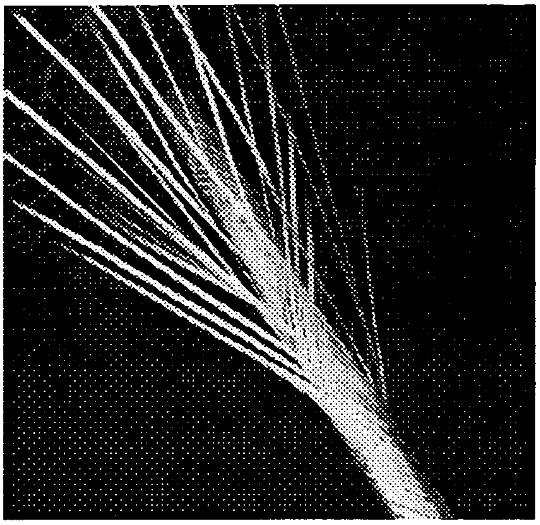

Fig. 2 Strong, flexible first-generation HTS wires are stranded together to form power transmission cables. (Courtesy of American Superconductor.)

drawing a billet of silver containing granules of BSCCO into thin filaments, which are then bundled and placed inside another silver tube to form bendable wire. The final cable, though thickened by silver and the nitrogen pipe, carries three to five times as much power as a copper cable of the same size – and this is at a still early stage of the technology. Significantly, Yurek went on to found American Superconductor.

BSCCOs are also of two types, the so-called 2:2:2:3 and 2:2:1:2 variants, the numerals referring to the proportions of the constituent elements. The former, seen as having potential applications in bulk superconducting power transformers, motors and power storage devices, is the formulation used by American Superconductor and others in first-generation wires. The latter type is best suited to use in magnetic booster coils and other low-temperature, high-field devices.

BSCCO superconductors, though potentially superior to conventional copper, have drawbacks. As well as mechanical fragility, there is a ceiling on the amount of current that can be carried and another on the level of magnetic field in which the system can be operated. The magnetic constraint is serious in transformers and other devices in which a magnetic field is central to the system's operation. (Cessation of superconductivity experienced with older low-temperature technology has, for instance, marred the operation of mag-lev train prototypes that have been trialed in Europe and Japan.) However, it has proved possible to produce working BSCCO conductors in kilometer lengths.

Many experts believe that the second HTS family, the rare-earth cuprates, with their higher critical current that survives stronger magnetic fields, are the best choice for future second-generation wire and derivative products. But so far their polycrystalline, granular structure has thwarted attempts to produce wires or tapes in useful lengths. Grain boundaries within the material constitute weak links to the flow of electric current, limiting the distance over which superconductivity can be maintained. Strategies for circumventing the grain boundary problem include developing large grain, essentially monocrystalline forms, and manipulating the boundaries of fewer, larger grains to be largely parallel, leaving paths for the flow of current. Processes now exist for forming large-grain materials having boundaries aligned within the required 4-5°, but the challenge of finding the most affordable route remains.

Having the right substrate can help in achieving the required grain characteristics. Nickel wire is widely favored, not only because it can be fabricated in kilometer lengths at low cost, but also because it can be textured to encourage formation of appropriately structured superconductor material. Proprietary substrates have been launched; best known being the Rolling Assisted Biaxially Textured Substrates (RABiTS) from ORNL, which are now used as the basis for several wire and tape products. Intermediate 'buffer' coatings are also essential to help integrate the top layer of the superconductive coating with the substrate and to prevent contamination between the substrate and the superconductor.

A decade ago it was discovered that a thin film of a rare earth cuprate material could be applied to metal substrate by physical vapor deposition (PVD). The Japanese company Fujikura has succeeded in producing superconducting tape in lengths of tens of meters in this way. Los Alamos and ORNL have likewise pursued chemical solution developments, although so far conductor properties lag behind those yielded by physical routes. MCT, working with ORNL, has developed an open-atmosphere process called combustion chemical vapor deposition, CCVD (though it is not strictly CVD), with which it can deposit material, both HTS and buffer, onto nickel wire or single crystal oxide substrates to produce wire. MCT expects this method to minimize the use of expensive

silver applied with vacuum processes in first-generation wire. Its process will further reduce costs because, according to MCT, it lends itself to continuous feed processing, necessary for viable wire production. In addition to growing epitaxial films of complex oxide on nickel successfully, MCT scientists Shara Shoup and Subu Shanmugham have deposited CeO_2, yttrium stabilized zirconia (YSZ), and other complex oxides onto $LaAlO_3$ and MgO single crystal substrates. By offering a combination of these processes and RABiTS (licensed from ORNL) to commercial partner Southwire, MCT aims to deliver the ingredients for a cost-effective HTS product. Manager of the ORNL superconductivity programme, Robert Hawsey, was pleased with the results achieved by the public-private sector research partnership. The collaborators are now targeting in their R&D efforts a critical superconducting temperature of 90 K and critical current of 1×10^6 A/cm^2.

Other efforts to bond rare-earth cuprate superconductor materials to substrates have targeted melt and liquid coating methods, in the hope of cutting cost. David Cardwell of the Interdisciplinary Research Centre in Superconductivity at Cambridge University is working on the growth of large grain magnetic material structures for levitation-type applications. Judith Driscoll at Imperial College, together with Xiaoding Qi, has developed novel liquid coating processes for growth of the buffer and superconducting layers [1]. Driscoll is hopeful about her team's liquid coating processes. The buffer layer can be grown very rapidly and simply, directly onto a Ni-alloy substrate. A thin, intermediate NiO layer is formed at the interface, which is compatible both with the Ni-alloy and cuprate buffer. The superconductor film has the required grain-free characteristics and can be grown with very good properties to a thickness of a few microns. "The coating of the YBCO layer is a non-exotic process well-known in the semiconductor industry," says Driscoll, whose work has recently been patented and will be presented at the American Ceramic Society's annual meeting this month. "Its promise is such that we now have a fully funded three-year programme, in collaboration with Jan Evetts' team at Cambridge University, to develop our route further. The main challenge now is scaling up the technology to levels consistent with volume production." A liquid phase epitaxy (LPE) system, with no need of a high-vacuum component, is cheaper to build compared with CVD systems and provides high growth rates. Key to its use on a metal substrate is the prior laying down of a buffer layer of neodymium cuprate (interestingly,

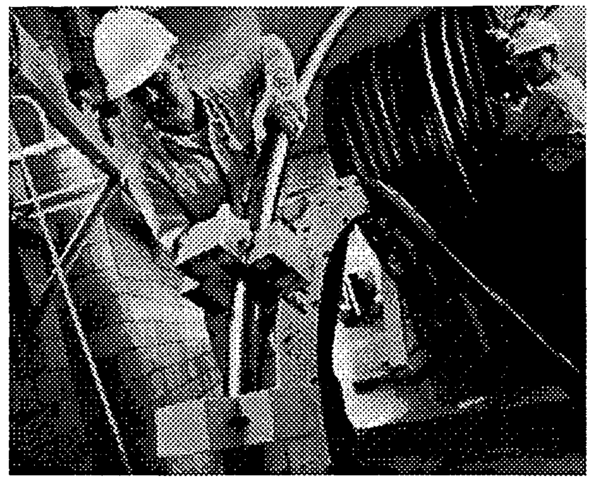

Fig. 3 Installation taking place at Frisbie sub-station. (Courtesy of American Superconductor.)

this material is itself a superconductor when cooled below 25 K) by screen printing, dipping or melt-processing. Driscoll says that this easily applied thick-film buffer is a significant innovation with implications across a range of HTS manufacturing techniques.

Electrical engineers hope that such processes can help reduce the capital and operating costs of using superconductor devices because they are eager for the benefits. For example, unlike conventional large copper wire-based power transformers, which are cooled by oil and have to be located outside on hard standings massive enough to support their weight, superconductor equivalents would use liquid nitrogen which, as well as being a cheap, widely available commodity, is intrinsically safe. These much lighter cool-running units could be installed indoors safely, near to the point of power use. Other substantial markets are expected for HTS-based fault current limiters for use in grid supply applications, and superconducting magnetic energy storage (SMES) devices. In transport, rail locomotive producers are investigating HTS transformers for reducing grid voltages of typically 25 kV to a working level of several hundred volts. These, in contrast to today's transformers that dominate a locomotive in terms of size and weight, would be small and light, so improving efficiency and reducing wear.

Researchers everywhere were astounded by the recent discovery in Japan of an inexpensive, commonly occurring compound that can superconduct at 39 K. Cardwell believes

that the magnesium diboride discovery[2] suggests that this may not be the only commonly occurring material able to superconduct, and others may be found, which can operate at liquid nitrogen temperatures.

Cost

Cost remains a dominant barrier to the widespread exploitation of superconducting materials. HTS have helped, and fabrication processes are becoming more affordable, but there is still a gap between what is currently possible and what is commercial. Driscoll suggests that, while technologies already discovered can deliver costs in the order of \$100/kA-m, this is still over three times the \$30/kA-m widely regarded as viable. American Superconductor believes that economies of scale in its new factory will enable it to reduce costs from the present \$200/kA-m level to a more acceptable \$50/kA-m over the next few years. This will happen as production volume grows, from a planned 3000 km this year to some 20 000 km/year eventually. Paul Grant of the Electric Power Research Institute expects that, allowing for the costs of running a refrigeration system, cables will eventually bottom out at two to three times the cost of conventional copper cables of the same power capacity. According to Grant[3], "None of the problems of superconducting cables now outweigh the benefits. We are at the point where it is worth running superconductors and everyone is beginning to realize it."

Cost benefit analyses might indeed soon start to come out in favor of superconductors. The DOE estimates that electric utilities using HTS equipment could save as much as \$2.5 billion by reducing resistance losses. (Typically only 0.5% of power is lost during transmission using superconducting cables compared with 5-10% lost by traditional cabling.) Small wonder that, for three years running during the Clinton administration, the department pumped \$40 million into superconductor research. Last year a report from the US National Energy Policy Development Group recommended that 'the President directs the Secretary of Energy to expand the Department's research and development of superconductivity'.

In the UK, the privatized National Grid is more cautious and says it has no firm plans at present to use superconductor technology, but is keeping a keen eye on developments. As network engineer Mark Osborne points out, "It will be years before the benefits can have an impact at high voltages, 132 kV and above, which are our primary interest. Superconductivity is more likely to contribute in lower voltage situations, like that at Detroit." He stresses the need to be realistic when taking into account full life cycle costs. "We don't yet know about all the problems associated with engineering and keeping cryogenic systems effective, leak-free and reliable over a 20-40 year service lifetime."

Agreement is widespread, however, that major locality infrastructure renewal costs can potentially be avoided by using HTS cables underground in areas where extra power is needed, but there is no space for additional copper lines. With demand for electricity predicted to double by 2030, superconductive cables could be crucial. In shipping, where a major transition to electric propulsion is taking place, a predicted annual market of \$2-4 billion could be served largely by superior compact motors based on HTS technology. Generators in power stations could evolve similarly. Overall, industry analysts forecast that the entire market in the US, Europe, and Japan for superconductor products and services could be worth \$122 billion by the year 2020.

It is over 90 years since Dutch physicist Heike Kamerlingh Onnes showed that the electrical resistance of mercury when cooled below 4.2 K dropped to zero and the metal became superconducting. The promise offered by his discovery has yet to be met and the key that could truly unlock its potential, a practical superconductor able to work at room temperature, is still to be found (though the recent reported observance of the effect in carbon nanotubes by various researchers is intriguing).

Meanwhile, the appearance of commercially viable HTS wire, tape, and disc products on the market within the next two or three years may prove to be just in time. The fact that the window of largest opportunity, that in electrical power distribution and storage, may not last long, means that continued research funding, diligence and luck, allied with a sense of urgency, are vital. This time, superconductivity could make it, big time! MT